

AUG 29 2006

ATTORNEY DOCKET: PD-02W202
PATENT

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Utility Application of:

Kalin SPARIOSU, et al.

Serial No.: 10/771,047 : Group Art Unit: 2828
Filed: February 2, 2004 : Examiner: Jeffrey D. Lane
For: SCALABLE LASER WITH ROBUST PHASE LOCKING

Commissioner of Patents
P. O. Box 1450
Alexandria, Virginia 22313-1450

AFFIDAVIT UNDER 37 CFR 1.131

Sir:

We hereby declare that we are the inventors of SCALABLE LASER WITH ROBUST PHASE LOCKING disclosed and claimed in the above-identified Patent Application.

Enclosed herewith is a copy of an invention disclosure, which shows that the invention was conceived by us before October 8, 2003. We continued to work diligently on the invention from conception to the filing of a Patent Application on February 2, 2004. Our conception and work on the invention occurred in the United States of America.


We hereby declare that all statements made herein of our own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under 18 U.S.C. 1001 and

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that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

FULL NAME OF JOINT INVENTOR Kalin SPARIOSU	INVENTOR'S SIGNATURE 	DATE 8-23-06
RESIDENCE (Full Address) 1262 Calle De Oro, Thousand Oaks, California 91360		CITIZENSHIP USA

FULL NAME OF JOINT INVENTOR Alexander A. BETIN	INVENTOR'S SIGNATURE	DATE
RESIDENCE (Full Address) 1246 8 th Street, Manhattan Beach, California 90266		CITIZENSHIP USA

- 2 -

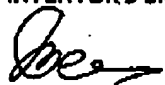
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RESIDENCE (Full Address) 1262 Calle De Oro, Thousand Oaks, California 91360		CITIZENSHIP USA

FULL NAME OF JOINT INVENTOR Alexander A. BETIN	INVENTOR'S SIGNATURE 	DATE 8/28/06
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- 3 -

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Serial No.: 10771,047

Raytheon**Invention Disclosure
Questionnaire**

10-5876-2PC (8/00)

**Raytheon
Proprietary**

Complete the information in the spaces provided. Use the TAB key to advance to the next field. Shift-TAB will move the cursor back one field. Either X or Space-bar can be used to check boxes where required.

Prepare the Invention Disclosure Form, except for the information on page 3. The original should be signed and witnessed where indicated. Send the original and three copies directly to the Regional Patent Engineer (see below). Have a copy reviewed and annotated by your department manager (through your immediate supervisor), and then by the manager of the program office or business area most likely to benefit from protection (via patent or trade secret) of your invention. Once you receive the appropriate comments and signatures, the executed copy and six additional copies should also be sent to the Regional Patent Engineer at (see attached instructions):

Inventors at ELCAN, ROSI, and sites in CA or AZ: Intellectual Property & Licensing Dept., Raytheon Company, 2000 East El Segundo Blvd (EO/E01/E150), El Segundo, CA 90245; Texas area: Intellectual Property & Licensing Dept., Raytheon Company, 13510 N. Central Expressway, M/S 200, Dallas, TX 75243; Northeast Region: Intellectual Property & Licensing Dept., Raytheon Company, 141 Spring Street, Lexington, MA 02421.

1. TITLE OF INVENTION

High power Er:crystal fiber-based laser with robust coherent phase locking technique

2. INVENTOR(S) (If more than 3, identify additional inventors in Section 14 and check this box ☐)

(A) NAME (first, middle, last)	EMPLOYEE ID	PHONE	FAX NO.	COMPANY & SEGMENT	DEPT NUMBER
Kalin Spariosu	1021842	310-647-0947	310-647-3250	Raytheon ES	23C725
HOME ADDRESS (street, city, state, zip) 1282 Calle De Oro, Thousand Oaks, CA 91360		CITIZENSHIP US	COMPANY MAIL/ADDRESS 2000 E. El Segundo Blvd. Bldg E1, M/S D109, P.O.Box 902, El Segundo, CA 90245-0902		
E-MAIL: kalin_spariosu@raytheon.com		MANAGER Maurice Halmos			
(B) NAME (first, middle, last)	EMPLOYEE ID	PHONE	FAX NO.	COMPANY & SEGMENT	DEPT NUMBER
Alexander A Betin	HACR2271	310-647-4109	310-647-0806	Raytheon ES	23C701
HOME ADDRESS (street, city, state, zip) 1246 8th Street, Manhattan Beach, CA 90266		CITIZENSHIP US	COMPANY MAIL/ADDRESS 2000 E. El Segundo Blvd. Bldg E1, M/S D125, P.O.Box 902, El Segundo, CA 90245-0902		
E-MAIL: kalin_spariosu@raytheon.com		MANAGER Tom Hastings			
(C) NAME (first, middle, last)	EMPLOYEE ID	PHONE	FAX NO.	COMPANY & SEGMENT	DEPT NUMBER
HOME ADDRESS (street, city, state, zip)		CITIZENSHIP	COMPANY MAIL/ADDRESS		
E-MAIL:		MANAGER			

Patent Department will determine legal inventorship**3. PROOF OF CONCEPTION**

A. BY WHOM WAS FIRST DESCRIPTION WRITTEN OR DRAWING MADE? Alexander A Betin	DATE CONCEIVED 8-15-02	ACCT. CHARGED (TIME/MATERIAL) NP1ADH15B1	LOCATION OF FIRST DESCRIPTION / DRAWING (TECHNICAL NOTEBOOK NO. AND PAGES) S149-15R#2 Kalin Spariosu Note Book
B. TO WHOM WAS INVENTION FIRST DISCLOSED? Robert Byren	DATE DISCLOSED 8-20-02	MANNER OF DISCLOSURE Verbal with pictorial aid	

PATENTS AND LICENSING USE ONLY

High power Er:crystal fiber-based laser with robust coherent phase locking technique	DATE RECEIVED	PATENT DOCKET NUMBER
IP/INDSC REV. 5/1/2000	PAGE 1 OF 13	

4. REDUCTION TO PRACTICE

A. WAS A DEVICE EMBODYING THE INVENTION CONSTRUCTED AND TESTED OR THE PROCESS PRACTICED?	YES <input type="checkbox"/> NO <input checked="" type="checkbox"/>	BY WHOM	DATE STARTED	DATE COMPLETED	ACCT. CHARGED (TIME/MATERIAL)
B. PRESENT LOCATION OF DEVICE AND ALL DOCUMENTS SHOWING REDUCTION TO PRACTICE A2147A					

5. RELATIONSHIP TO GOVERNMENT CONTRACT

A. WAS THIS INVENTION CONCEIVED AND/OR REDUCED TO PRACTICE UNDER GOVERNMENT CONTRACT?	YES <input type="checkbox"/> NO <input checked="" type="checkbox"/>	CONTRACT NUMBER AND TITLE
B. TO ASSIST RAYTHEON IN COMPLYING WITH GOVERNMENT REPORTING REQUIREMENTS, PLEASE PROVIDE CONTACT IN GOVERNMENT AGENCY AND RAYTHEON CONTRACTS DEPARTMENT (IF KNOWN). none		

6. RELATIONSHIP TO COMPANY-FUNDED PROGRAM

A. WAS THIS INVENTION CONCEIVED AND/OR REDUCED TO PRACTICE AS PART OF A COMPANY-FUNDED PROGRAM/PROJECT?	YES <input checked="" type="checkbox"/> NO <input type="checkbox"/>	IDENTIFY PROJECT TITLE, NUMBER, ETC. High Energy Eye Safe Laser (HEESL) SE (NP1ADH15B1)
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7. RELATED DOCUMENTS

A. ARE THERE ANY RELATED INVENTION DISCLOSURES OR PATENT APPLICATIONS?	YES <input type="checkbox"/> NO <input checked="" type="checkbox"/>	IDENTIFY FILE OR CASE NUMBER, ETC.
B. ARE THERE ANY RELATED ISSUED PATENTS OR TECHNICAL PUBLICATIONS?	YES <input type="checkbox"/> NO <input checked="" type="checkbox"/>	IDENTIFY

8. USE, COMMERCIALIZATION AND FOREIGN MARKETS

A. ARE YOU AWARE OF ANY POTENTIAL COMMERCIAL APPLICATIONS FOR THE INVENTION?	YES <input checked="" type="checkbox"/> NO <input type="checkbox"/>	IDENTIFY POTENTIAL CUSTOMER, APPLICATION, TIME FRAME US Government. The applications of the device described in this invention disclosure range from compact airborne eye-safe lidar transmitters, large standoff eye-safe range finders, target detection and identification, to higher energy scaled versions for directed energy weapons.
B. ARE YOU AWARE OF ANY FOREIGN MARKETS FOR THIS INVENTION?	YES <input checked="" type="checkbox"/> NO <input type="checkbox"/>	IDENTIFY COUNTRIES, APPLICATIONS, TIME FRAME US and NATO allies will find use for this device in the military scenarios described above. In addition, commercial applications such as airlines equipped with active sensors for airport incursions avoidance, collision avoidance, detection and identification of adjacent aircraft will find uses for this device.
C. HAS THE INVENTION BEEN OR IS THE INVENTION TO BE INCORPORATED INTO A COMPANY PRODUCT OR PROGRAM?	YES <input checked="" type="checkbox"/> NO <input type="checkbox"/>	PRODUCT(S) OR PROGRAM(S), TIME FRAME Standoff lidar eye-safe transmitters (2005 time frame), directed energy weapon platforms - airborne and ground vehicular based (2010 time frame).

PATENTS AND LICENSING USE ONLY

High power Er:crystal fiber-based laser with robust coherent phase locking technique	DATE RECEIVED	PATENT DOCKET NUMBER
IP/INDSC REV. 5/1/2000	PAGE 2 OF 13	

9. DEPARTMENT MANAGER COMMENTS TO PATENT EVALUATION COMMITTEE

The importance of obtaining an efficient laser operating directly at eye-safe wavelengths stems from the need for a compact, robust all-solid-state laser source to fulfill a variety of airborne applications requiring operation at large stand-off ranges. In addition to ladar, range finding, and target ID functions, this type of laser can be scaled to weapons grade energy levels for tactical missile defense applications. A variety of airborne platforms that can incorporate weapon - grade lasers already exist; however, the current laser approach is the COIL laser. Among solid-state laser options, the Er laser would offer the most robustness since it operates at a wavelength where the human eye is several orders of magnitude more resistant to damage than at any other wavelengths.

NAME

SIGNATURE

DATE

PHONE

10. PROGRAM OR BUSINESS OFFICE COMMENTS TO PATENT EVALUATION COMMITTEE

See above.

Numerous eye-safe laser ladar, range finder and target ID applications are in need of a better beam quality, more compact, robust, light weight and cost effective laser that can be readily scaled higher powers / energies. The incorporation of this novel phase-locking technique that offers robust combining of a large number of Er:fiber laser oscillators allows for readily scalable energies for directed energy applications in addition to large standoff ladar applications.

NAME

SIGNATURE

DATE

PHONE

11. SUPERVISOR: please affirm the charge number and program data provided in sections 3, 4, 5, and 6 of this disclosure.

SUPERVISOR NAME

SIGNATURE

DATE

PHONE

PATENTS AND LICENSING USE ONLY

High power Er:crystal fiber-based laser with robust coherent phase locking technique

DATE RECEIVED

PATENT DOCKET NUMBER

IP/INDSC REV. 5/1/2000

PAGE 3 OF 13

TITLE OF INVENTION

High power Er:crystal fiber-based laser with robust coherent phase locking technique

INVENTOR(S) (Additional inventors may be listed in Section 14)

Kalin Spariosu

Alexander A Betin

12. PUBLICATION, SALE, OR PUBLIC USE

A. HAS THE INVENTION BEEN DISCLOSED TO A THIRD PARTY WITHOUT THE EXECUTION OF A NON-DISCLOSURE, PROPRIETARY, OR OTHER CONFIDENTIALITY AGREEMENT?	YES <input type="checkbox"/> NO <input checked="" type="checkbox"/>	DATE	TO WHOM
B. HAS THE INVENTION BEEN USED, DISCUSSED, DEMONSTRATED OR OTHERWISE DISCLOSED OUTSIDE THE COMPANY (SUCH AS TO A VENDOR OR CUSTOMER)?	YES <input type="checkbox"/> NO <input checked="" type="checkbox"/>	DATE	TO/FOR WHOM (COMPANY/PERSON)
C. HAS THE INVENTION BEEN SOLD OR OFFERED FOR SALE?	YES <input type="checkbox"/> NO <input checked="" type="checkbox"/>	DATE	TO WHOM
D. IS THERE A PUBLICATION OR PUBLIC PRESENTATION RELATED TO THE INVENTION? (This includes the Internet)	YES <input type="checkbox"/> NO <input checked="" type="checkbox"/>	DATE	IDENTIFY
E. HAS A MANUSCRIPT DESCRIBING THE INVENTION BEEN SUBMITTED FOR PUBLICATION?	YES <input type="checkbox"/> NO <input checked="" type="checkbox"/>	DATE	TO WHOM
F. IF THE ANSWER TO E. WAS YES, HAS THE MANUSCRIPT BEEN ACCEPTED FOR PUBLICATION?	YES <input type="checkbox"/> NO <input type="checkbox"/>	DATE	WHEN AND WHERE WILL IT BE PUBLISHED?

INVENTOR(S) SIGN AND DATE:

WITNESS NAME (PRINT)	WITNESS SIGNATURE	DATE	WITNESS NAME (PRINT)	WITNESS SIGNATURE	DATE
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High power Er:crystal fiber-based laser with robust coherent phase locking technique	DATE RECEIVED	PATENT DOCKET NUMBER
IP/NDSC REV. 5/1/2000	PAGE 4 OF 13	

13. SUMMARY OF THE INVENTION**A. STATEMENT OF THE PROBLEM SOLVED BY THE INVENTION**

There is currently a need for a compact robust solid-state laser operating directly at eye-safe wavelength(s) that is easily scalable to high average powers and high pulse energies for a variety of airborne applications. In addition, the implementation of a weapons-grade solid-state laser based on a eye-safe wavelength of operation is desired by the defense industry - and currently does not exist.

B. PRIOR ATTEMPTS OF OTHERS TO SOLVE THIS PROBLEM

The attempts to solve the compact eye-safe laser problem included Nd:YAG lasers with frequency conversions such as Raman and optical parametric oscillators (OPOs). These systems are inherently bulky and cannot be readily scaled to high energies as they require a very large number of pump sources to make a compact airborne platform integration impractical. Er lasers that lase directly at eye-safe wavelengths have traditionally been based on glass hosts which severely limits the thermal handling of these systems which in turn limits the power scalability. Although phase locking of multiple core fiber (MCF) lasers has been demonstrated, these systems rely on the Talbot effect (based on periodical structures) to phase lock. This phase locking technique is limited as it requires extremely precise length equalization of the individual cores and is highly dependent on the individual power output in each core. Furthermore, there is a limit how many elements can be locked in this way because of multiplexing issues in the common cladding. Namely, for adding tens of elements in a MCF type configuration, the Talbot effect would suffice; however, to extend the scaling to multi-kW powers will invariably require separate fiber laser oscillators. In that case, the Talbot effect by itself would not possess the required robustness to perform and effective phase locking.

C. HOW YOUR INVENTION SOLVED THIS PROBLEM

The approach we propose is the implementation of Er:YAG crystal fiber laser oscillators directly coupled and pumped by high power diode lasers. In this way high power diode laser arrays (comprising of several bars each) would have "pigtail" coupled Er:YAG crystal fiber oscillators which will subsequently be phase locked - combined - via a robust external cavity technique that does not rely on precise oscillator cavity lengths implementation and does not require identical individual element output powers to efficiently phase lock - combine.

D. WHY YOU BELIEVE THAT THE INVENTION IS NEW (Specifically point out all novel features)

To the best of our knowledge there are no other published reports of directly diode pumped Er:YAG crystal fiber lasers. Also, to the best of our knowledge, there are no published reports of the robust phase locking technique that can combine efficiently numerous fiber oscillators via an external cavity technique.

14. DETAILED DESCRIPTION.

Use the Invention Disclosure Continuation Sheet to provide a detailed written description of your invention, using as many pages as necessary. Be certain to include a description of the "best mode" or best means of practicing the invention known to you at this time. You may insert figures, tables, and photos into this section, or you can attach copies of relevant proposals, prior art, or other documentation that will assist the Patent Evaluation Committee in fully considering your invention. (Note: Please place information on additional inventors first in this section).

INVENTOR(S) SIGN AND DATE:

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High power Er: crystal fiber-based laser with robust coherent phase locking technique

DATE RECEIVED

PATENT DOCKET NUMBER

IP/NDSC REV. 5/1/2000

PAGE 5 OF 13

RaytheonInvention Disclosure
Detailed Description
10-5876-3PC (5/00)Raytheon
Proprietary

High energy solid-state lasers (Yb:YAG, Nd:GGG - 1 micron wavelength) are gaining ground in development towards achieving weapons-grade status. One obvious shortcoming for such lasers is the collateral damage it may produce to friendly forces. Namely, even with laser protection goggles, eye damage risks due to secondary and tertiary glint reflection could end up inducing permanent eye damage to friendly troops. Clearly, then, equivalent laser sources that would have many orders of magnitude higher damage thresholds would be critical for practical eventual implementation of such directed energy (DEW) systems.

Lasers operating in a narrow region from about 1.4 μm to 1.8 μm where the vitreous humor absorbs strongly exhibit several orders of magnitude increase in human eye damage threshold:

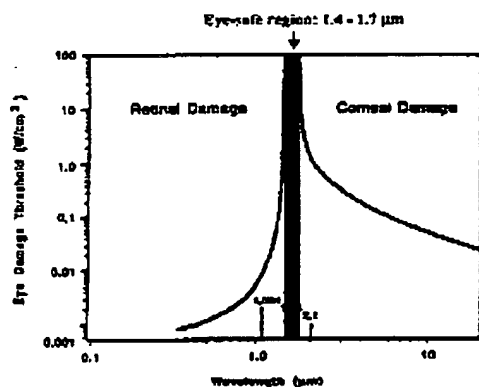


Figure 1. Eye damage threshold as a function of laser wavelength
(courtesy of Dr. Larry DeShazer)

Resonantly pumped Er:YAG laser, which lases directly within the "eye-safe" wavelength window, is very similar to the Yb:YAG laser: it is pumped directly into the upper laser excited state and has a small quantum defect ensuring high efficiencies and low thermal loading:

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IP/INDSC REV. 5/1/2000	Page 6 of ##	

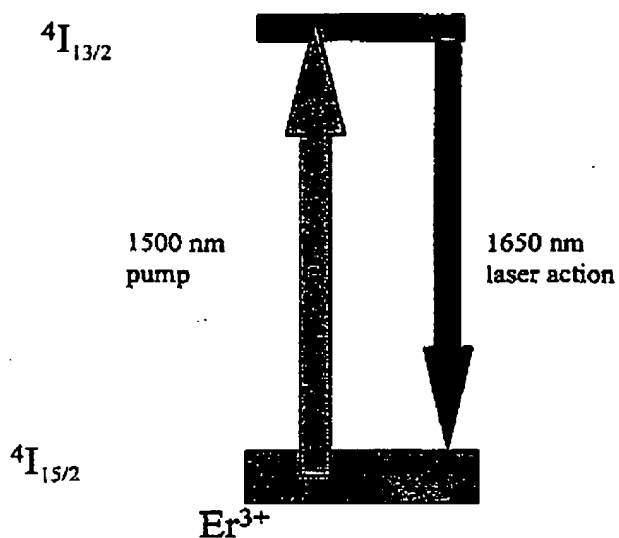


Figure 2. Resonantly pumped Er:crystal laser dynamics

Unlike Yb, however, Er does have upper lying energy levels, which could introduce parasitic losses due to upconversion and/or excited state absorption – as shown below:

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IP/INDSC REV. 5/1/2000			Page 7 of ##		

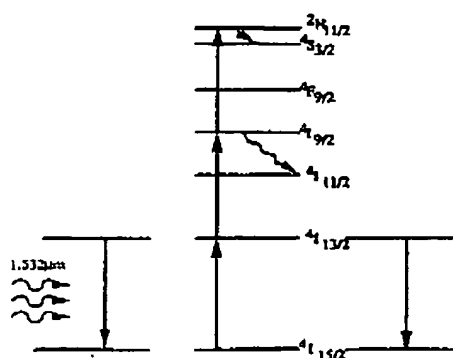


Figure 3. Er:crystal upconversion dynamics

This, fortunately only become significant at high Er concentrations^[1]. At small Er concentrations (< 0.5 % doping), the parasitic losses are insignificant and achievable optical-optical efficiencies can be as high as 50 %; however, the pump absorption is small requiring relatively long absorption lengths. In a standard laser at an eye-safe configuration, this becomes an issue also from the point of view of sensitivity to diode laser temperature dependent operating wavelength.

Our innovative high energy eye-safe laser approach leverages the following key features of the Er:YAG laser gain medium:

- Resonantly pumped highly efficient low Er concentration gain medium
- High absorption efficiency and insensitivity to temperature variations in an elongated Er:YAG fiber structure (YAG fiber synthesis was demonstrated^(2,3)).
- Excellent energy storage capability of Er:YAG (even better than in Yb:YAG lasers), but higher gain than in Er:glass and negligible re-absorption (since in YAG host Er is essentially a quasi-four level laser). This drastically reduces red-shifting which can affect the overall stability of the phase locker.
- Scalable to multi-kW power levels via phase phase locking technique without compromising the modular pump-fiber laser structure.
- Direct diode pumped – multiplexed system with inherent compactness and integration flexibility.

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IP/INDSC REV. 5/1/2000

Page 8 of ##

- Thermal management-friendly laser configuration inherent in fiber lasers / amplifiers

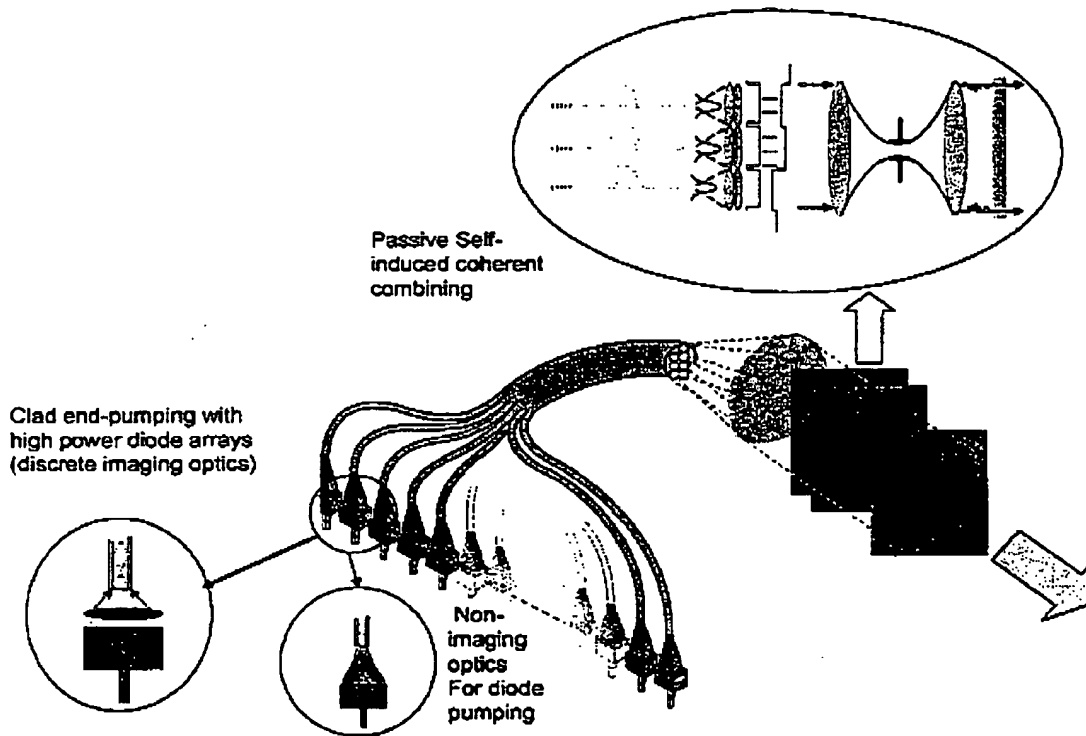


Figure 4. Er:YAG fiber laser system showing modular structure scalable to multi-kW power levels.

The pump sources are diode laser arrays with kW-level power capability. These diode pump arrays are coupled to the fibers via inner cladding either in an end-pumped configuration or side-coupled. The individual Er:YAG crystal fiber laser oscillators have integral back reflectors that will allow for the necessary feedback in the coherent combining feedback cavity. The detailed end-cladding - pumped arrangement is shown in Figure 5 below:

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IP/INDSC REV. 5/1/2000			Page 9 of ##		

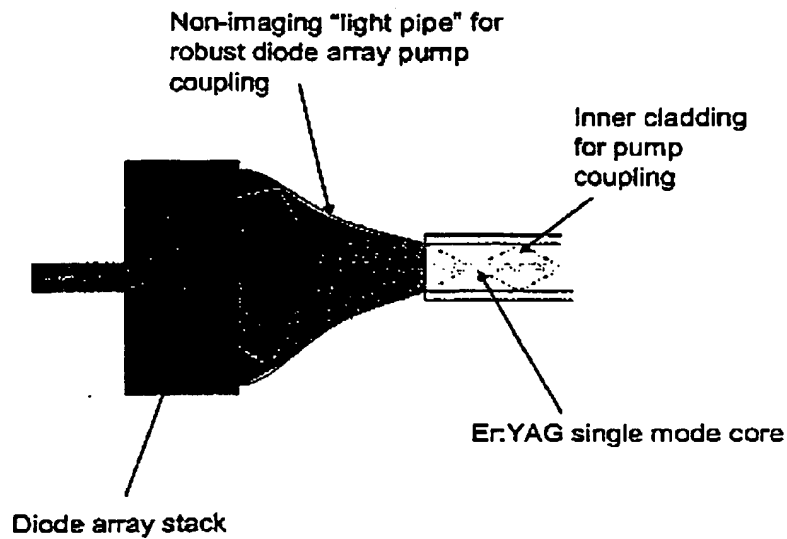


Figure 5. Diode array end pumping in the double clad fiber structure.

The implementation of a compact pumping arrangement where the pump diode array sources are coupled into a reflective disk structure for efficiently capturing all the pump light is shown in Figure 6 below:

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IP/INDSC REV. 5/1/2000			Page 10 of ##		

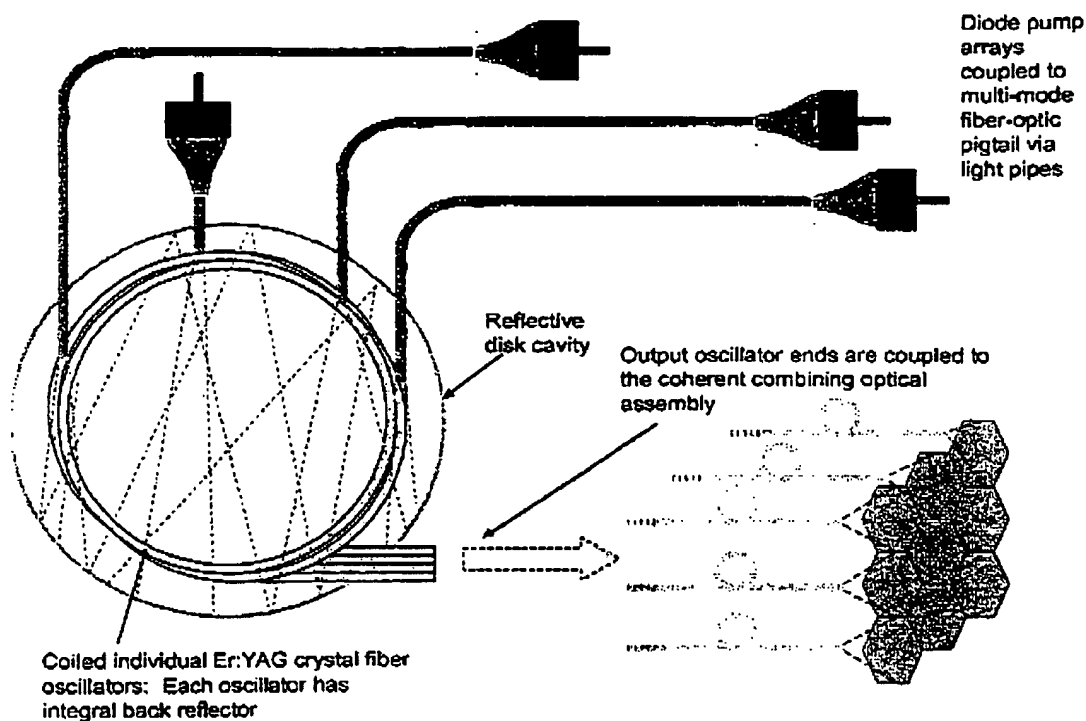


Figure 6. Integrating pump cavity based on a reflective disk that provides for a compact packaging of the individual Er:YAG crystal fiber oscillators as well as ensuring 100% pump absorption.

The coherent combining / phase locking cavity arrangement is described in Figure 7 below:

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IP/INDSC REV. 5/1/2000			Page 11 of ##		

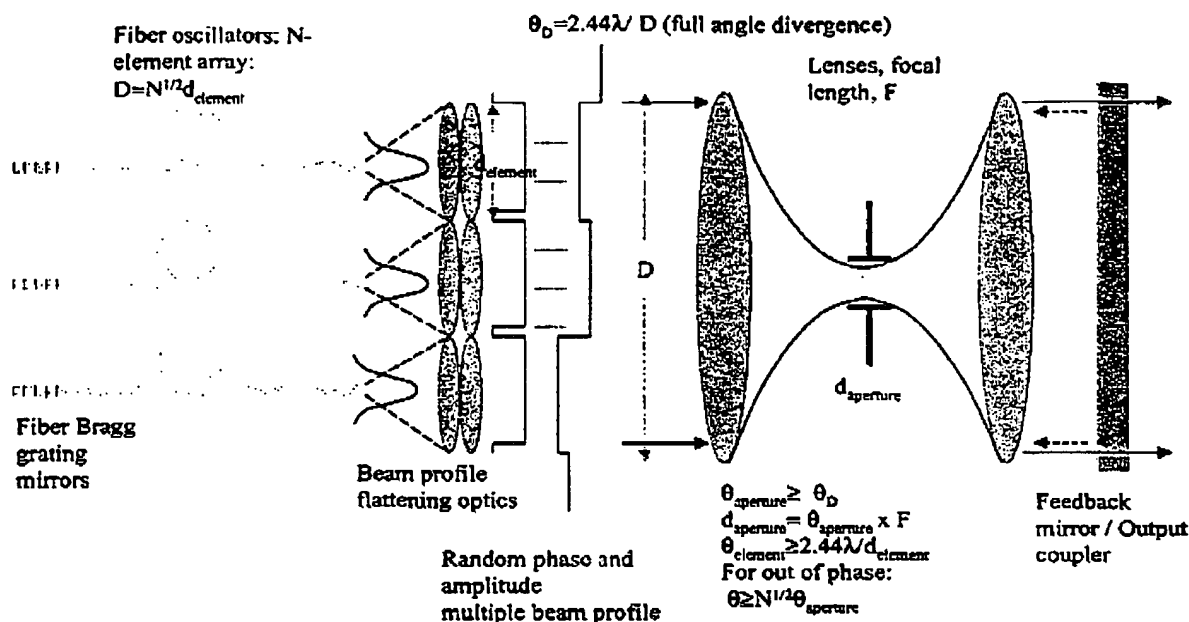


Figure 7. Coherent combining / phase locking cavity arrangement that provides for a highly robust passive phase locking approach that does not depend on stringent dimensional control of the individual oscillators.

The individual fiber lasers will have a random phase and amplitude profile as shown above. The collimating lenses for each of the individual oscillators will provide for top hat intensity profiles. Placing an aperture in the transform plane of an external cavity lens pair followed by a feedback mirror / output coupler will ensure that only the field components that are in phase will exhibit significant feedback as the completely out-of-phase components will be lossy and, therefore, suppressed. The aperture can either be a simple pin-hole type aperture for only the fundamental mode feedback, or a fitted (matched) aperture with side lobes generation. The diffraction of the entire system – assuming single phase matched wave front – is based on the effective aperture size of the collimating lens pairs.

D. The coherent diffraction angle is then $\theta_{\text{coherent}} = \frac{2.44 \lambda}{D}$, and the spot size is $d_{\text{coherent}} = \theta_{\text{coherent}} \times F$, where F is the focal length of the common lenses. It clearly follows that for the individual elements, the diffraction angle – in the non phased case – is

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Title from disclosure form Inventor's Names separated by commas			DATE RECEIVED	PATENT DOCKET NUMBER	
IP/INDSC REV. 5/1/2000			Page 7 of ##		

$\theta_{\text{element}} = \frac{2.44\lambda}{d_{\text{element}}}$ (this could be $\theta_{\text{element}} = \frac{2\lambda}{D}$ in the case of a true square symmetry). Since in a symmetrical 2-D arrangement of

M elements, $D = \sqrt{M} d_{\text{element}}$, the diffraction angle for the non-phased array is $\theta_{\text{non-phased}} = \sqrt{M} \theta_{\text{coherent}}$ and $d_{\text{nonphased}} = \theta_{\text{nonphased}} F$.

It clearly follows that with the facilitation – allowance – of phase and frequency locking, only the least lossy – phased – condition will dominate, as the out-of-phase components will exhibit a much higher loss and will, therefore, be suppressed. The relative transmission (per pass) of the non-phased mode is $T = (d_{\text{coherent}} / d_{\text{nonphased}})^2$. Clearly, the completely non-phased mode will be extremely lossy and will not be sustained. The partially phased locked modes – even with only a small fraction of the oscillators out of phase will see a reduction in transmission – hence – gain and will be suppressed. For the target number of – say – 100 oscillators, the scenario of even one pair of oscillators being out of phase will result in a ~2 % loss per pass. This is still a viable operation condition for the implementation of phase-locked operation.

in order to efficiently fill the two-dimensional space within the external cavity, a hexagonal mirror geometry could be implemented as shown in Figure 8 below:

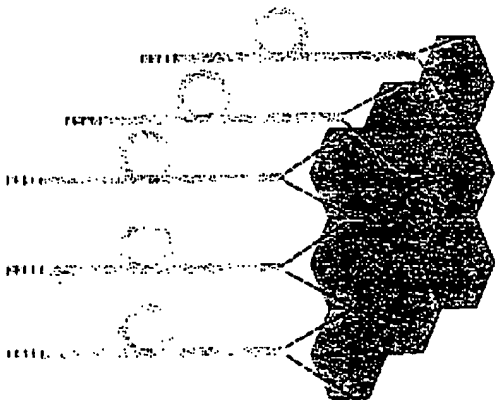


Figure 8. Efficient high fill factor implementation of the two dimensional Er:YAG fiber oscillator array.

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IP/INDSC REV. 5/1/2000	Page 8 of ##	

As stated earlier, this collimating lens array could transform the Gaussian TEM₀₀ mode coming out of the single mode fiber oscillators to a flat top with >95 % efficiency which would be sufficient to facilitate efficient phase locking of the individual oscillators.

In order to effect phase – coherent – locking of individual fiber oscillators two conditions need to be satisfied:

1. The oscillators must operate with frequencies $\omega_j = \omega$ within the gain bandwidth, and
2. The phases of the individual oscillators must match: $\varphi_j = \varphi$.

To achieve the first condition, one possible solution is to make the individual fiber oscillators of identical length. Although, one can in principle make the fibers identical in length, the oscillator cavity which is comprised of the the free space length from the fiber ends to the common output coupler is difficult to make exact in length for all the oscillators because of mechanical / thermal issues. Hence, making the fibers deliberately different in length with sufficient deviation such that frequency – longitudinal mode - overlap will occur within the gain bandwidth of the laser oscillation.

In a long cavity length oscillator of length, L, the mode-spacing defined by the resonator cavity is $\Delta\nu = \frac{c}{2L}$ or in terms of wavelength: $\Delta\lambda = \frac{\lambda^2}{2L}$. Here c is the speed of light and λ is the center (peak) laser wavelength. For a 2 m long resonator, the longitudinal mode spacing (for the 1645nm laser peak wavelength) is ≈ 0.007 Angstroms. For the typical linewidth of the Er:YAG transition of up to 1 Angstrom, the gain profile will support about 148 modes. As the length of these fibers varies, so does the mode spacing. For a length difference of >1.4 cm (for the 2 m long fiber), there will be mode overlap between the two dissimilar length oscillators - free spectral range (FSR) is exceeded for these length differences. For longer fiber oscillators (example 3 or 4 m), the length variation condition (for exceeding the FSR and ensuring mode overlap) of >1.4 cm still holds true since the number of modes increases with increasing fiber resonator length (221 modes for 3m long and 295 modes for 4 meter long resonators). Hence the mode spacing is reduced and the FSR is maintained for a particular length variation. Therefore, either ensuring precisely equal lengths of the YAG crystal fiber oscillators, or deliberately making these oscillators with varying lengths with length differences exceeding 1.4

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cm will ensure that all oscillators will be capable of longitudinal mode overlap – hence capable of phase locking. Because Er:YAG crystal exhibits a sharp gain profile (unlike glass), the spectral purity of the overlapped –phase locked oscillator is maintained, so that no additional etalons are required to limit the “wavelength wander” of the individual oscillators.

The phase differences of these individual oscillators can be described as: $\varphi_j = \varphi_n$ and $\varphi_{j+1} = (N + f) \frac{2\pi}{\lambda} L_{oscillator}$, where $f < 1$ and N is an integer. That is, typical phases differences between adjacent oscillators will vary by many 2π cycles, thus ensuring that phase locking can be facilitated at some equal phase condition $\varphi_n = f \frac{2\pi}{\lambda} L_{oscillator}$ beyond the $N \frac{2\pi}{\lambda} L_{oscillator}$ full cycle offset. The

phase fluctuations in the different oscillators can be expressed in terms of refractive index fluctuations: $\delta\varphi_j = \delta n_j \frac{2\pi}{\lambda} L_{oscillator}$ where

$\delta n_j = \frac{\partial n}{\partial P_{oscillator}} \Delta P_{oscillator}$. A number of mechanisms can lead to δn depending on the active material, geometrical factors and so

on. Typically, the change in the electron population among the various energy levels in an active lasing media will lead to a change in refractive index. In addition, slight changes in the heat distribution will also lead to a refractive index change. For instance, a

conservative change in refractive index as a function of temperature of $\frac{\partial n}{\partial T} \approx 10^{-5}$ will result in a phase difference of $12.16 \times 2\pi$, or

$N = 12, f = 0.16$ for a 1°C temperature change. Thus, clearly, phase locking of the individual oscillators will easily be facilitated in this system.

This phase locking techniques for combining many individual oscillators can also be applied to Yb:glass fiber lasers/amplifiers, micro-lasers arrays, and semiconductor lasers. Depending on the particular gain media, intra-cavity etalons can be added in order to restrict the gain profile (for instance, in glass hosts and semiconductor lasers, the gain profile is typically much broader than in crystal host laser.)

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IP/INDSC REV. 5/1/2000	Page 10 of ##	

The coherent combining concept presented above features:

1. Completely passive – self induced phase locking
2. Insensitive to even large fluctuations in the path length of the individual oscillator elements (such as due to mechanical, thermal and acoustic interference).
3. Does not require precise alignment of the phase locking cavity because of the robust nature of this approach.
4. Not limited to Er:YAG crystal fiber lasers, but applicable to any laser oscillator system including slab laser oscillators

Prior art for phase locking laser oscillators arrays (including fiber laser structures) is based on the Talbot effect ^[4-9]. This approach requires a highly sensitive / precise path length alignment and maintenance so that practical implementation of this technique is limited. In cases where the precise path length problem within the gain medium is controlled such as is the case with multi-core monolithic fiber-optic structures ^[4, 5, 8], the problem / difficulty is transferred to the power scaling limit because the heat extraction efficiency is again limited to a single monolithic fiber structure. Independent of utilizing the monolithic structures, the Talbot effect still suffers from high sensitivity to path length perturbations in the external cavity mirror portion.

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Page 12 of ##

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